FACILITY FORM 602

N66-17476
(ACCESSION NUMBER)

45
(PAGES)

CR 70458
(NASA CR OR TMX OR AD NUMBER)

(THRU)

1
(CODE)

[redacted]30
(CATEGORY)

[redacted]

GPO PRICE $ _____

CFSTI PRICE(S) $ _____

Hard copy (HC) 2.00

Microfiche (MF) .50

ff 653 July 65

"TYCHO" STUDY GROUP

ELECTRICAL ENGINEERING DEPARTMENT

UNIVERSITY OF MINNESOTA

FINAL REPORT

of the

"TYCHO" STUDY GROUP

1965

Contract No: NSR-24-005-047

Prepared By

UNIVERSITY OF MINNESOTA

Minneapolis, Minnesota

for

Headquarters, National Aeronautics and Space Administration
Washington, D. C. 20546

December 15, 1965

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I. Conclusions and Recommendations

When the results of the study were examined by this Group, a set of recommendations became apparent. These recommendations encompassed several different points of view--all, however, within the general framework of defining the lunar surface with sufficient detail to assist the Apollo program. Some of the recommendations are for additional Earth space laboratory experiments, some for additional examination of data already on file, and several for proposed possible experiments which would further aid in describing the nature of the surface of the Moon. Several, however, are the result of a clear recognition that remote sensing of the unfamiliar terrain will not enable an accurate prediction of bearing strength to be made. This difficulty is a direct result of the fact that the interaction of electromagnetic radiation with the lunar surface does not sense those collective effects that play a role in mechanical bonding of structures.

The recommendations of the Group are as follows:

A. "TYCHO" feels it essential that a back-up experiment to the present Surveyor program be given high priority. The Surveyor vehicle represents sophisticated, complex engineering and one may reasonably expect difficulties, especially early in the program. We strongly recommend that a back-up experiment involving either a soft landing vehicle with a larger degree of tolerance or a hard landing vehicle in which nothing

other than measurements of a surface property such as density or bearing strength be attempted. The recently proposed Sandia impact probe is an example of such an experiment.

B. The landing point should be selected to minimize the danger to the astronauts from the point of view of current models of the lunar surface. For instance, the floor of a 50 to 100-meter wide new "crisp" crater seems to offer best possibilities as discussed further on Page 19. Infrared cooling anomalies, radar reflectivity, and optical back-scatter give independent evidence of locations of high surface density. Further, all equipment and plans should be made compatible with all the models and training should take place in sand and above all in light "fluff" in vacuum.

C. Because of its importance to the Apollo program, behavior of the dust in a high vacuum and its influence on the performance of the mission equipment in such an environment should be the core of an extensive experimental program. This is particularly important because there is no doubt that there is some dust on the lunar surface since the infall of meteorites alone would pulverize any surface material.

D. All photometric studies of the lunar surface and some of the infrared, radar, and radiometric studies measure in effect the properties of the lunar dust layer. For this reason a wide systematic program of measurements of various properties (mechanical properties, coherency, dielectric constant and losses, thermal conductivity, light scattering and polarization) of lunar dust substitutes under possible realistic conditions (solar wind, irradiation, churning, temperature variations, vacuum conditions, etc.) should be initiated. Preliminary experiments have already shown that many of these properties change in a drastic manner under these conditions.

E. Laboratory verification of a lunar surface brightness and polarization model outlined in Appendix VII of the Report of the August 1965 "TYCHO" Meeting (TG #1) which shows that the backscatter intensity and the polarization can determine surface density and particle size should be attempted. If the model is verified, backscatter at small angles versus position on the Moon should indicate fluctuations in surface density and thus porosity. This will be helpful in choosing a suitable landing site.

F. The lunar orbiter program should include an active radar satellite as well as the proposed photographic system.

G. At present the only ground-based method of probing the variation of the surface material with depth seems to be radar studies as a function of wavelength and polarization. Such studies thus far have been carried out in detail only for 23 cm wavelength and should be carried out for additional wavelengths.

H. The infrared data indicate regions of high thermal transport (harder regions) which overlap, within limits of resolution, regions of high radar reflectivity. The experimental results of these two programs should be examined to obtain a common surface model paying particular attention to the difference in predictions based on a homogeneous or nonhomogeneous surface and on a layered or a graded surface.

I. The proposed thermal mechanism of lunar luminescence suggests under what conditions this effect should be observable. Systematic ground-based observations should be made to test this model and to indicate possible variations of the mineral content on the surface.

J. Much has been said concerning laser beams to probe the contour of the lunar surface to determine its gross figure. This

experiment at the present would require an advance in laser technology and its successful conclusion would not contribute greatly to answering urgent questions about the lunar surface. Information obtained from the lunar orbiter will be far more useful. Such a program, therefore, should not be undertaken at this time.

II. Aspects and Comments on Present Knowledge of the Lunar Surface

A. Introduction

The spectrum of models proposed for the lunar surface ranges from a surface entirely covered by a dust layer of varying thickness to a surface which is completely volcanic in origin. The reasoning and conclusions made by various workers in this field are often completely contradictory. In this section an outline of conclusions drawn from observation will be presented and distinction will be made between those conclusions supported directly by evidence and those less certain which are chiefly an opinion and inference.

In considering the lunar surface it must be realized that up to the present all data available concerning the lunar surface were obtained through remote sensing. For the purpose of planning a lunar landing, it is unfortunate that the coupling of electromagnetic radiation to solids samples their dielectric and not mechanical properties. The lack of atmosphere and the presence of a flux of micrometeorites produce conditions which are sufficiently different from most laboratory experiences that conclusions drawn from analogy are highly questionable. It is, therefore, useful to examine critically the observations and the conclusions that can be made.

Historically, the optical telescope has been used to establish gross topographic features. The high resolution cameras used in the Ranger missions permit mapping of topographic contours and obtaining frequencies of occurrence of

various features down to perhaps one meter. Nevertheless, no conclusions about the physical nature of the Moon can be made without drawing on analogies with terrestrial conditions.

The measurements of scattering and polarization of reflected sunlight as a function of wavelength yield surface density and particle size. These results lead without question to a surface covered with a very fine dust, finer than is encountered in the lightest known sandy terrain.

The absolute magnitude of the thermal emission detected in the infrared region or the spectrum can be used to establish the surface temperature of the Moon. From the variation of this emission during a lunar eclipse the thermal inertia of the first centimeter can be inferred. These results suggest that the very porous low density material extends at least to about 1 cm. Detection of the emission at radio frequencies can also be used to establish a temperature. In this case the depth sampled is comparable to a wavelength which for the frequencies used is several centimeters. These results also indicate a very low density material.

The reflection of radar pulses from the Moon directly measures the dielectric constant and infers a "smoothness" and density of the surface. In this case the dielectric constant is the average over about a meter depth of material. These experiments show that the lunar surface material has a low dielectric constant which when compared to Earth rocks implies a low density. The value of porosity (i.e. fraction of voids)

thus obtained is 0.7 which is considerably higher than that of sand. The radar reflection has been also used to infer "smoothness." This type of analysis is possible, but uniqueness has not been established.

In summary, the established methods of observing the lunar surface--optical, radar, infrared, and radio emission--do not permit drawing direct definite conclusions about the strength of the surface. Estimates based on the assumption of a weakly coherent micron size dust give a lower limit approximately 6 gr/cm^2 (12 lb/ft^2) and a value ten times higher for a more strongly bonded (partially sintered) dust. For higher loads sinking will commence.

B. Discussion

1. Surface Topography

The surface topography has been the source of the most extreme conflicts in the interpretation of lunar observations. The fundamental facts which must be understood are the existence of large, flattish, dark lowlands or Maria; the existence of more rugged, brighter highlands; the existence in both these areas of vast numbers of craters extending in size from hundreds of kilometers to meters; the morphological features of these craters (the various shapes of crater rims and crater bottom contours, the crater outlines and relief, the long linear depressions in some crater interiors, the existence of radial rays extending many diameters from some craters, etc.) and other general patterns such as regions of differing color

in Maria and the apparent local preferred directions for linear features. On Earth, topography has been shaped by castrophic volcanims, and later by the atmospheric and hydrospheric erosion. To a lesser extent, the Earth also bears the marks of meteorite bombardment.

The origins which have been suggested for craters are a) volcanism and associated geological activity, and b) meteoric impacts (with possible secondary impact from ejecta). The only evidences of origin are the number of craters and their morphology. The number and size distribution of craters smaller than 10 kilometers is in approximate agreement with the current rate of meteoric impacts on Earth and the age of the Moon. Volcanism, on the other hand, does not provide means of predicting the number or size distribution. The scale of typical lunar craters is about ten times larger than that of known large Earth caldera.

Some craters have raised, hummocky rims, while others have softer, rounded features. This could be due to a) erosion or b) different origin for different forms of craters (e.g., meteoric impacts for raised rim craters, and secondary impacts and/or slumping for softer features). Erosion requires an erosion mechanism while slumping requires a weak sub-surface structure, (e.g., voids in lava flow).

An estimate of the minimum amount of erosion possible during the lifetime of the Moon can be made from the meteor infall rate on Earth. At least a meter depth of the surface

would have been broken into rubble by this means and the upper few centimeters would have been pulverized by micrometeorites. The micrometeoritic bombardment alone guarantees the presence of at least a thin "dust" cover of very small particles. Conservation of energy demands that most of this rubble does not escape from the Moon. There are other erosion mechanisms for softening lunar features, such as weathering of rock under the influence of ultraviolet light, the solar wind bombardment and extreme temperature cycling. The rather small relief of most large craters is the strongest support for a major erosion mechanism.

The Maria and many large craters have floors generally very flat, and apparently covered with a flow of some kind of material different from the highland material. This material could be a) the product of erosion, chiefly dust or b) the product of volcanism, lava and/or ash flows. (Lava surfaces produced in the absence of an atmosphere are expected to be very different from those produced on Earth.) Color differences in these regions have been either preserved or generated by the surface material. An electrostatic mechanism of levitating dust to allow erosion and dust migration has been suggested but it could suspend only <u>extremely</u> small particles.

The existence of long, soft shouldered, linear depressions on crater floors and their alignment with respect to crater rims and other features has generally been taken to indicate that such features are a natural result of subsurface structure and

movement. Such features could result from volcanism or from stress due to a changing lunar rotation speed. Slump features could be due to the withdrawal of magma, the appearance or the disappearance of ice, or the failure of weak rock (e.g., an underdense lava).

Many associations present in terrestrial caldera are present in the general features of lava craters, e.g., associated craterlets around the inner edge of a crater; crater peaks, etc. The high degree of circularity possessed by most of the lunar craters, especially the larger ones, is not typical of Earth caldera.

Bright rays often extend many crater diameters from a crater. These rays have been considered as either a) lava or ash flows, or b) the pattern of ejecta from an impact crater. Ranger photographs indicate the presence of swarms of soft-shouldered craters in these rays. Discussions based on flow patterns or projectile ballistics for particular rays are useful, but all ray effects are not necessarily of one origin.

The following description will account for all the general topographical features, including the few existing quantitative data:

> The primary source of craters is meteoric impact. Magmatic activity has also been present on the Moon; the filling of the "older" flat crater bottoms and Maria is due to lava. The linements and slump

features are due to this magmatic activity. Erosion by bombardment rounds off all features of the order of a few meters, and has produced a general layer of rubble and dust whose thickness depends on the age of the area. For old areas, this should be the order of a meter, and the top of this layer is a very finely divided material.

2. Photometry and Polarimetry

Most regions of the Moon are brightest at full Moon, and the Moon as a whole looks uniformly bright. The back-scatter peak is an effect of shadow. The interpretation of this sharpness requires a material which is 90-98% empty space, and these empty spaces must be interconnected and the material itself must be opaque. The polarization of the reflected sunlight from the Moon has been measured as a function of lunar phase. It is interpreted as an effect of the finite wavelength of light. It provides a measure of the linear dimension of the particles of filaments of this material which turns out to be the order of 10^{-3} cm. The color and albedo of the lunar surface is too strongly influenced by the solar wind to yield reliable conclusions about the chemical nature of the material. While the conclusions from the photometry and polarization studies seem secure, the measurements refer only to an optical depth, a distance of about 10^{-2} cm.

3. Infrared and Microwave Emission Measurements

The infrared measurements determine the temperature within 10^{-2} cm of the surface. A study of the surface temperature as a function of time during varying illumination conditions provides a measure of "kρc." This parameter is connected both to the filling, decreasing as the empty space increases, and also to the degree of contact between particles, decreasing as the contact decreases. While a simple interpretation of all such results has not yet been possible, $\sqrt{k\rho c}$ of typical lunar areas is about a factor of 30 smaller than for solid rocks. From these infrared measurements one can infer kρc appropriate to the first few centimeters of material. The evidence obtained for a second deeper and denser surface from attempting to fit cooling curves is not conclusive. A material consisting of perhaps 70% empty space, and not too well bonded (e.g. crushed basalt) would be consistent with the observed kρc.

Microwave emission measurements also yield a lunar temperature, but the effective depth of this temperature is in this case a few centimeters. There is unfortunately no a priori method of determining from Earth the effective microwave depth in lunar material. While this has limited the quantitative interpretation, these data do not contradict the infrared work. Microwave emission has also been interpreted to obtain the dielectric constant (see also Para. 5).

The infrared measurements demonstrate the existence of small areas which heat and cool more slowly than

typical lunar material. These areas can be identified as small sharp craters which appear optically bright and usually have raised rims. These areas are in some sense more tightly packed, at least to a depth of the order of a centimeter. The physical aspect of such craters has sometimes been described as "looking young."

4. Celestial Mechanics Observation

The analysis of lunar dynamics has given good values for the mean lunar density and for the ratios of the three lunar moments of inertia and an approximate value for the absolute value of the moment of inertia. All these are of great interest in the geology of the Moon. Of these, the mean mass is probably the most significant at present, for it gives an indication of the elemental composition of the Moon, its radioactive heat generation, and therefore on the possibility of lunar melting. Although this has been a subject of some controversy, it now seems impossible to avoid a Moon which was partially melted and had the possibility of volcanism during its lifetime. A better knowledge of the absolute moment of inertia would give much needed additional information about the internal structure of the Moon.

5. Radar Studies

Present-day radar techniques allow a map of the radar brightness of the Moon to be constructed at a resolution capable of observing geographical lunar features. The radar brightness is measured at backscatter (transmitter-Moon-

receiver angle of zero) and return strength is related to the dielectric constant, which gives a measure of the lunar density, and to the surface roughness. The dielectric constant, as measured from the overall radar return, is consistent with a lunar surface consisting 70% of voids. The range of wavelengths over which the data have been obtained suggest that this figure is appropriate to at least the first 50 cm. (The radar effectively does not see the optical layer.) A distribution of surface slopes has been obtained. Such a distribution does not, unfortunately, give much indication of the topography. A certain percentage of "surface roughness" is deduced but whether this roughness is on the surface or indicates the presence of inhomogeneities below the surface cannot be ascertained. Polarization measurements on the lunar limbs have been interpreted as consistent with a surface dielectric constant of 1.8 but the interpretation is not unique.

The radar return from specific lunar regions shows that sharp-featured craters, especially ray craters are often bright radar reflectors. This increased brightness could be due either to an increased surface roughness or an increased density at the surface.

C. Summary

Undoubtedly the question of paramount practical importance of the present time is the nature and the mechanical strength of the lunar surface in the flat regions. There are many observations which permit an estimate of the

apparent density, particle size, dielectric constant, and even thermal conductivity of the uppermost layer of the surface but none of them lead to an unambiguous evaluation of the degree of compaction, cohesion, and differentiation with progressive depth. Without these no sensible calculation of the mechanical properties, as they effect soft landing and the mobility of astronauts, is possible. Attempts were made to by-pass these difficulties by evaluating in a semi-quantitative manner certain details of the Ranger photographs. The underlying models are, however, too arbitrary to consider the results as definite indications of the mechanical characteristics of the surface. One concludes, therefore, that at present we have no reliable information about the mechanical strength of the lunar surface in the flat regions and that it is essential to make direct measurements. Such measurements can be made using penetrometers for instance such as those most recently proposed by Sandia Corporation. The proposal is particularly attractive because it supplies information about a whole area rather than about the point of impact only. These measurements should preferably precede and at least augment the Surveyor and are absolutely necessary for a sensible design of LEM and for the safety of the astronauts.

There was and still is a considerable diversity of scientific opinion concerning the presence or absence of <u>dust</u> on the lunar surface. Even among those who are in favor of a dust layer, there is a great difference in the estimates of the

thickness of this layer in the flat regions. This latter question is intimately related to the problem of the amount of erosion which has occurred and occurs on the Moon. Here again, the opinion ranges from a complete negation of erosion to the opposite extreme of concluding that the erosion was so great that the resulting dust layer must be up to several kilometers deep. The strongest and deciding quantitative argument in favor of erosion and of the resulting dust layer is the known influx of meteorites and micrometeorites and the experimentally investigated results of such impacts. The presence of dust finds confirmation in the photometric, radar and thermal data which do not seem to be in agreement with the assumption of highly porous "sponge-like" solids. In any case, the latter would be turned into dust by the meteoritic infall in a very short time. There is thus no doubt that erosion exists and that highlands are covered with a relatively thin layer (at least several millimeters) of rather cohesive dust. For the same reason, one is led to the conclusion that flatlands (Maria and bottoms of craters) are also covered with dust and that because of much lower slopes the layer is appreciably thicker than on the highlands. This conclusion is independent of any considerations concerning the origin and nature of the underlying material (lava, ice) in these areas. No unambiguous estimate of the dust layer on the flatlands exists although thermal observations clearly indicate that certain specific areas are rather bare. These can be identified by large thermal

inertia and they are usually associated with "crisp" bright, "new" craters of various sizes. No convincing arguments seem to exist against erosion and against the presence of at least some dust. Considerations based on crater counts are weak because of the ambiguity of the criteria used in the crater selection for statistical methods.

Another problem about which many contradictory statements have been made is the question whether the Moon ever was or still is hot or molten inside. The arguments for and against this volcanism are usually qualitative and highly subjective. Especially those based on analogy with terrestrial features are subject to doubt because of a difference of orders of magnitude in size and because of the known rapid erosion on Earth. The circularity of lunar craters or its absence, the central features in craters, the presence or absence of a correlation between craters, their size and other features is, at present, too qualitative to be convincing one way or another. The strongest arguments in favor of a hot Moon and of some volcanic activity are a) various numerous cracks and faults in the lunar surface which seem not to bear any relation to craters b) striking differences in color and their relatively sharp boundaries within Maria and c) theoretical calculations based on a variety of plausible assumptions concerning the history and the radioactive composition of the Moon. While the spectrum of evidence for and against volcanism is wide and diversified, the weight of evidence presently available seems

to lean towards a hot Moon and towards a certain amount of restricted volcanic activity. The bottoms of many craters, especially the larger ones, are undoubtedly filled with lava although the craters themselves are meteoritic in origin.

The choice of an appropriate place to soft land on the Moon involves several considerations. Obviously, one should choose a place which is possibly safe for the astronauts rather than one which is close to some interesting features. While highlands are probably hard rock, the evidence indicates they are covered with a low porosity material (dust). In any case, their unevenness seems to involve too much of a risk for a landing site. The other two kinds of areas are the Maria and the bottoms of craters. The nature of the Maria and the depth and strength of the probably quite thick dust layer are at present too poorly known to provide a sufficient factor of safety. This conclusion could be changed of course if definite and favorable information were to be obtained from penetrometers as discussed above. Thus, at present the floors of craters seem to offer the best possibility for minimizing the dangers of a deep loose dust layer. In order to make the right choice, one should use topographical and thermal criteria. Topographical features which appear to be indicative of low erosion and thus of a relatively thin dust layer are for example "crispness" and brightness of the crater rim and a size between 50 and 100 meters. The lower size limit is suggested to facilitate a

proper landing and to provide easy access to the rim. The upper limit came from the preference for a crater which is not filled with lava which may have been pulverized to a large depth. The thermal criterion is related to the strikingly high thermal inertia of certain craters which are usually but not always of the "crisp" bright kind mentioned previously. It is almost certain that a local high thermal inertia is indicative of a thin dust layer which exposes the underlying rock and permits observing its different thermal characteristics.

III. SUMMARY OF RESEARCH CONTRIBUTIONS

(Note: The following comments pertain to research contributions prepared by "TYCHO" Study Group members and published as appendices in the Report of the August, 1965, "TYCHO" meeting -- Report No. TG #1.)

Nearly all present knowledge about the Moon is based on observation of reflected or emitted electromagnetic radiation (visible, infrared and radar) from its surface. The paper by J. J. Hopfield, "Interpretation of the Brightness and Polarization Curves of the Moon," (Appendix VII) gives a theoretical treatment of the backscattering and polarization of visible light at small phase angles. It is shown that optical data can give the density and particle size to an optical depth of lunar dust layer if the theoretical model is verified in laboratory experiments. The polarization curve at small angles is interpreted in terms of shadow effects for micron size particles rather than in terms of Mie's theory.

Present lunar data on brightness and polarization is consistent with the calculations for a porosity in the range of 85-98%, and for particle size of about 10 microns.

Results of radar investigations are described in J. V. Evans' paper "Radar Studies of the Moon" (Appendix III). At normal incidence some 60% of the radar energy at decimeter wavelengths is reflected from the surface whose uppermost layer has an effective dielectric constant of not less than 1.8 which implies a porosity in the range 70 - 90% depending upon the nature of the material. For a two-layer model proposed to account for polarization experiments the dielectric constant of the base layer must be 4.5 - 5.0 and the material

quite compacted if not solid while the depth of the upper layer must be greater than 23 cm. The lower boundary is presumed to be rougher than the upper one and 20% of the base layer is assumed to be covered with structure of the order of the wavelength in size. Limitations of the model are discussed.

Some of the observations described in Evans' paper pertain to radar echoes from the lunar limb. The problems of their theoretical interpretation are discussed in H. Suhl's paper, "Some Considerations Concerning Radar Returns from the Lunar Limb," (Appendix XII). Radar backscatter of small objects on a dielectric or conducting plane is analyzed in terms of their dependence on wavelength, polarization and angle. The calculated λ^{-2} dependence on wavelength and $\cos \phi$ dependence on angle for large angles is in reasonable accord with the experimental data. The limb polarization produced by such objects is negative and in agreement with experiment. The predicted wavelength dependence is capable of distinguishing this model from Hagfors' model.

"Electromagnetic and Thermal Properties of the Moon's Surface," (Appendix VIII) are discussed by B. Lax to show that a great deal of information can be obtained by remote radar and infrared measurements from the ground. The evidence indicates a layer of density of the order of 1.0 gm/cm^3 or porosity of about .70 (or filling factor of .3) for a depth of the order of a meter or more. According to measurements on

loose basalt powder an object of a given diameter will sink to a depth equal to this diameter in a powder of the calculated porosity under a load of 35 gr/cm^2 or 75 lbs/ft sq. There appears to be a gradient of density near the surface which is not well defined by present theory or experiments but is suggested in terms of a two-layer approximation by many investigators (see above).

Much of the present structure and nature of lunar surface is the result of impact of meteorites and micrometeorites, of solar wind and of solar electromagnetic radiation. In his paper, "Erosion on Lunar Surface by Meteor Impact," (Appendix II), R. J. Collins makes a quantitative estimate of erosion caused by the meteoritic infall. He concludes that for craters of radius less than $\sim$ 300 meters, the lunar surface is in steady state. Agreement was satisfactory between the infall rates with the proposed erosion model and the observed data.

The highest flux of all matter falling on the lunar surface is due to the micron size micrometeorites. "The Evidence for Particulate Matter in Space and its Potential Accretion Rate by Moon and the Earth" (Appendix IX) is discussed by E. P. Ney. Data on the F-Corona of the Sun, the Zodiacal light, and the direct measurements of fluxes of microparticles on the Earth's surface, lead to lunar acquisition of interplanetary particulate matter of about 30 Å per year. If the figure is correct, it is necessary for the incoming particulate matter to stir up approximately 300 times its own

mass of lunar material in order to account for the lunar erosion. It seems that the input of micrometeorites to the Moon is not in itself a serious source of lunar surface acquisition. If the present flux had existed throughout 10^9 years, a total of 300 cm of density 1 material would have been acquired from the interplanetary environment.

Solar wind and micrometeoritic impacts affect the "Structure of the Lunar Dust Layer" (Appendix XI) as discussed by R. Smoluchowski. On the basis of experimental evidence, it is concluded that solar wind can sinter fine dust by producing displaced atoms which diffuse towards the surface of the grains. The micrometeoritic churning of the topmost layer of lunar dust excludes sintering through sputtering. The dust is thus probably partly cohesive (0.5 dyne per particle) which increases its mechanical strength and decreases its mobility. Its lower layers are compacted by meteoritic bombardment and a close packed density is reached probably at a depth of a meter or so. Depending upon the degree of sintering, loads of a few to a few tens gr/cm^2 will not commence to sink in the topmost dust layer.

During the lunar day, the Moon changes to a positive potential due to the photoelectric effect. This "Potential and Electric Field at the Surface of the Moon" (Appendix VI) is evaluated in a paper by H. Heffner. Assuming a photon flux (below 4000 $\mathring{A}$) of $2 \cdot \times 10^{16}$ photons per cm^2 per sec, quantum efficiency 10^{-3} and 3 ev for the kinetic energy of the photo-

electrons one obtains a potential of 30 volts, a space charge layer of some 8 meters and an electric field of 1.6 volts/cm. These day time, normal incidence, values are lower for a more realistic, two orders of magnitude lower flux.

The electric field calculated in the previous paper may lead to "Levitation of Dust on the Surface of the Moon" (Appendix V) as discussed also by H. Heffner. It is shown that: a) photoelectric space charge effects are not sufficient to raise dust particles from the surface of the Moon, b) submicron dust particles can be suspended if they are raised to a sufficient height by micrometeorite impact, c) an appreciable fraction of these particles will be suspended as long as the angle of incidence of solar radiation is not too low, and d) under the influence of radiation pressure particles tend to migrate towards the shadow region. Charged dust particles may be a cause of much nuisance, if not danger, to an astronaut especially if he should happen to fall. Experimental tests are recommended.

Much interest and controversy has been raised by reports of excess lunar brightness. The pertinent "Mechanisms for Lunar Luminescence" (Appendix X) are discussed in a paper by E. P. Ney, N. J. Woolf, and R. J. Collins. It is shown that the visibility of luminescence on the Moon depends on the competing processes that illuminate the Moon and that provide energy for luminescence. Most favorable times for seeing luminescence are at new Moon on the far side of the Moon, and

during rare dark eclipses. The luminosity and color of these rare eclipses is explained. Direct processes for converting energy to luminescence in lunar day cannot be energized by presently known sources of particles. If storage processes occur they may give information about the dust particles at the extreme lunar surface.

The question whether the Moon was ever molten has been widely discussed. In D. L. Anderson and R. A. Phinney's paper the "Internal Temperatures of the Moon" (Appendix I) are analyzed in considerable detail and the related problem of volcanism is investigated by thermal history calculations. While the results depend on the radioactivity and age of the Moon, extensive interior melting is difficult to avoid. The chondritic Moon will start to melt at depths below about 300 km at about 1.9 billion years after formation. If the Moon has the composition of the Earth's mantle, melting will commence at about 1.6 billion years at a corresponding depth and will proceed rapidly inward. A moon with about 2/3 of the Earth's radioactivity and only 3.5×10^9 years old will not yet have melted if it started cold.

The most extensive stage of volcanism will probably follow differentiation, perhaps 2-3 billion years ago. It follows that the presence of lava and/or ash flows on the surface of the Moon is highly probable. The Moon is probably a differentiated body; but since iron is not involved in the differentiation, a heavy core is not present. It is also shown

that Mars will probably not melt and is now an undifferentiated body. This supposition is supported by the moment of inertia of Mars. It is suggested that the presently planned studies be expanded to include a lunar geodectic orbiter, a direct measurement of surface heat flow and a passive lunar seismometer. It is recommended that the feasibility of a monocycle radar pulse orbiter experiment to determine the structure of the outer several kilometers of the Moon be investigated.

In "The Case Against Volcanism" (Appendix IV) T. Gold argues that volcanism could not have been the major agency in shaping the primary features of the Moon. He suggests that ice sheets covered with dust are responsible for the flat mare and crater bottoms.

In Part II of his paper, T. Gold emphasizes the importance of high quality photography needed in future lunar exploration and the associated problems and peculiarities to be encountered in lunar photography.

IV. BACKGROUND OF THE "TYCHO" STUDY GROUP

A. Origin

On May 26, 1964, Mr. Homer E. Newell, Associate Administrator for Space Science and Applications, NASA, addressed a memorandum to the Deputy Administrator and to the Associate Administrator of NASA proposing that a group of approximately 20 established scientists be assembed on a part-time basis to study advanced physical problems in science as they relate to man's efforts in space exploration. This group would be free to address itself to new research areas, avenues of pursuit, and to matters of science of its own choosing. The group would consist of high caliber scientists recruited from academic and research areas primarily involved in solid state and theoretical physics. The emphasis on physics was sponsored by a need for solution of a number of physical problems encountered in the lunar program. Continuity of the group would be maintained over several years through retention of as many members as possible from year to year and through frequent sessions of several days duration in addition to an annual five to six weeks summer study session. Preliminary discussions between Mr. Newell, Mr. Willis B. Foster, Director of the Manned Space Science Division, Dr. Willard S. Boyle of Bellcomm and Dr. Robert J. Collins of the University of Minnesota in May, 1964, led to submission of a proposal by the University of Minnesota to organize and administer such a group.

The University of Minnesota's proposal was essentially consistent with the preliminary memorandum of May 26, 1964, and the discussions held at NASA headquarters. The proposal suggested expansion of the membership to include several members from other disciplines to provide cognizance of research activity and state of knowledge in related areas such as astrophysics, geology and microbiology and to include a representative from NASA headquarters for guidance on broad NASA programs and plans. Pressing lunar exploration problems would be reflected in the initial constitution of members selected for the study group who would also have demonstrated previous competence in research and scientific matters. The proposal emphasized need for orientation of members on problems under study and a general state of the art. It was planned that the location of the study groups should be removed from the usual working place of participants to avoid conflict with routine demands of their regular duties.

The University of Minnesota acts as the agency to supply fiscal responsibility and administrative organization for the study group. Administrative details are managed by an administrative officer assigned to a staff position delegated by the University of Minnesota.

The Study Group was initially called "The Manned Space Science Study Group." However, in August, 1965, in order to avoid confusion with other similarily entitled groups and organizations, the name was changed to "Tycho" Study Group

after the lunar crater "Tycho" which had figured in much of the research work conducted by the study group.

B. Members

The selection and recruitment of members to serve with the "Tycho" Study Group has been a more difficult task than anticipated. It was recognized at an early date that recruitment of well-known authorities in this area was futile because of the many demands for their services and their inability to devote extended periods of time with the group. Rather, it was decided to call upon such individuals for short presentations and special consultations as needed and when available. Dr. Gerard P. Kuiper and Dr. Eugene M. Shoemaker are examples of individuals in this category. Accordingly, it was then necessary to detect and recruit scientists who possessed significant potential for space research, but who, for a variety of reasons, had not yet achieved such widespread recognition for their work. Next, it was important to determine their motivation for this type of research activity and their availability to function with the group. The following is a list of members who have agreed to serve with the "Tycho" Study Group although several were unable to devote their full time to the summer study session in Boulder this summer:

Name	Institution	Principal Discipline and/or Area of Interest
*Allen, Frederick G.	Bellcomm, Inc.	Solid State Physics
Anderson, Don Lynn	Calif. Inst./Tech.	Geophysics
Collins, Robert J.	Univ. of Minn.	Solid State Physics
*Evans, John V.	Lin. Lab., MIT	Radar
#Gold, Thomas	Cornell Univ.	Astronomy
Heffner, Hubert	Stanford Univ.	Electrical Engineering
Hopfield, John J.	Princeton Univ.	Theoretical Physics
#Lax, Benjamin	MIT	Solid State Physics
#Ney, Edward P.	Univ. of Minn.	Astro-Physics
*Pearse, C. Arnold	Bellcomm, Inc.	Theoretical Physics
#Phinney, Robert A.	Princeton Univ.	Geophysics
Smoluchowski, Roman	Princeton Univ.	Solid State Physics
Suhl, Harry	Univ. of Calif./LJ	Theoretical Physics
#Woolf, N. J.	Princeton Univ.	Astronomy

*Participated part time and without monetary reimbursement.

#Participated part time as follows:

Gold	(One week, August 1-7)
Lax	(Three weeks, August 12-31)
Ney	(Two weeks, August 3-15)
Phinney	(Two weeks, August 9-21)
Woolf	(Three weeks, August 2-18, 26-28)

The following individuals particpated as special consultants:

Name	Institution/Company	Principal Discipline	Date
Green, Jack	North American Aviation	Geology/ Geochemistry	8/5&6
Shoemaker, Eugene M.	U. S. Geology Service Flagstaff, Arizona	Astronomy/ Astrogeology	3/27
Shorthill, Richard W.	Boeing Aircraft Corp.	Astrophysics/ Infrared	8/2&3

Commander Trygve A. Holl, U. S. Navy (Retired) has been retained by the University of Minnesota as Assistant Director for the "Tycho" Study Group and has functioned as the Administrative Officer since January 8, 1965.

C. Meetings

A preliminary meeting was held in Washington, D. C. on December 18, 1964, to clarify the purpose of the study group, to outline a plan of action, and to evaluate individuals who might be invited to participate as members in the group. At this meeting it was decided to proceed with plans for short interim meetings in March at Kansas City, Missouri, in conjunction with the American Physical Society meeting. It was also decided to schedule the extended summer study session during the month of August at a location to be determined later. The following individuals attended this meeting although several (Wertheim and Herring) were unable to continue as members of the study group:

Collins, Robert J.	University of Minnesota
Heffner, Hubert	Stanford University
Herring, W. Conyers	Bell Telephone Laboratories
Hopfield, John J.	Princeton University
Ney, Edward P.	University of Minnesota
Suhl, Harry	University of California

The second meeting of the study group was held at Kansas City, Missouri, on Saturday, March 27, 1965, to capitalize on the presence of a number of the members who were already in Kansas City attending the March meeting of the American Physical Society earlier that week. The purpose of this meeting was to

familiarize members with the Surveyor and Lunar Orbitor programs through a presentation by Dr. Martin J. Swetnick, Lunar Orbiter Program Scientist, OSSA, NASA, and receive a presentation by Dr. Eugene M. Shoemaker, Head, Astrogeology Branch, U. S. Geological Survey, Flagstaff, Arizona, on the state of optical data currently available through astronomy and the Ranger Program. The time and place of the extended summer study session was set at this meeting to be August 2 through September 3 at the University of Colorado campus in Boulder, Colorado. In addition to Dr. Swetnick and Dr. Shoemaker, individuals attending this meeting were:

Collins, Robert J.	University of Minnesota
Evans, John V.	Lincoln Laboratories, MIT
Franken, Peter A.	University of Michigan
Holl, Trygve A.	University of Minnesota
Hopfield, John J.	Princeton University
Ney, Edward P.	University of Minnesota
Pearse, C. Arnold	Bellcomm, Inc.
Suhl, Harry	University of California, LJ
Thompson, Wm. B.	Bellcomm (observer only)
Woolf, N. J.	Princeton University

Note: Dr. Franken has been invited to participate as a member of the study group but has not yet accepted because of other pressing commitments. This is the only meeting he has been able to attend to date.

A two-day meeting was held in Chicago, Illinois, on November 12 and 13 to review results of the extended summer session, to receive additional indoctrination on the Apollo program and other related lunar activities, and to discuss areas of concentration for the coming year. All members except Dr. Thomas Gold and Dr. Edward P. Ney attended this meeting. Dr. Richard J. Allenby, Deputy Director, Manned Space Programs, OSSA, attended this meeting as the NASA representative to brief the group on the Apollo program and other related lunar activities.

Meetings are tentatively scheduled to be held in January and March or April. The extended summer study session will be scheduled for the five-week period August 1 through September 2, 1966.